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# **(HBCU) DOPED GRAPHENE AND GRAPHITE AS A POTENTIAL HIGH TEMPERATURE SUPERCONDUCTOR**

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Final Report**

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# **Final Performance Report for FA9550-10-1-0134**

**to:**

**Dr. Harold Weinstock**

## ***(HBCU) DOPED GRAPHENE AND GRAPHITE AS A POTENTIAL HIGH TEMPERATURE SUPERCONDUCTOR***

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**23 July 2013**

## **I. Results on doped Highly Oriented Pyrolytic Graphite:**

In our first year we observed possible superconductivity using standard resistance vs. temperature techniques in phosphorous ion implanted Highly Oriented Pyrolytic Graphite. The onset appeared to be above 100 K and quenching by an applied magnetic field was observed. Four boron implanted samples showed no signs of becoming superconductive whereas all four initial and eight subsequent samples that were implanted with phosphorous showed at least some sign of the existence of small amounts of the possibly superconducting phases. The observed onset temperature is dependent on both the number of electron donors present and the amount of damage done to the graphene sub-layers in the Highly Oriented Pyrolytic Graphite samples. As a result the data appeared to suggest that the potential for far higher onset temperatures in undamaged doped graphite existed.

This work was published in Superconductor Science and Technology as a rapid communication (G. Larkins, Y. Vlasov, "Indications of superconductivity in doped highly oriented pyrolytic graphite," **Superconductor Science and Technology** 24 (9), 2011) and has received a number of citations.

These results led us to work on thin graphene peels exfoliated from Highly Oriented Pyrolytic Graphite samples. These results are summarized in section II below.

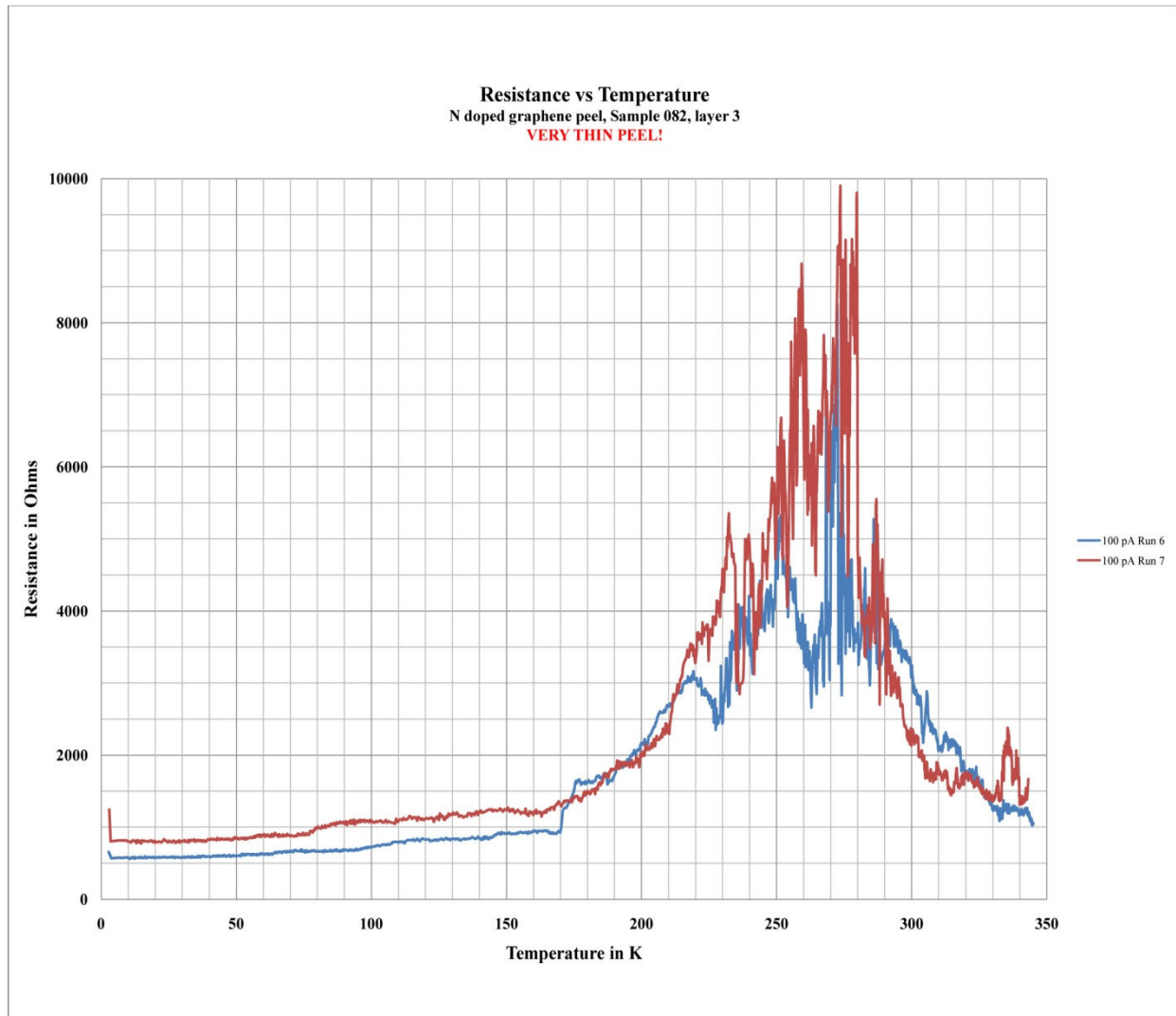
## **II. Results on Graphene Exfoliated from Highly Oriented Pyrolytic Graphite:**

We observed periodically repeated steps in the resistance vs. temperature characteristics of doped graphite and graphene using standard resistance versus temperature techniques in donor doped Highly Oriented Pyrolytic Graphite and exfoliated doped multi-layer graphene. The observations consist of a series of regularly spaced steps in the resistance vs. temperature curves. The lowest step is observed at a temperature of from 50 to 60 K. Additional steps are observed at multiples of that basic temperature with the highest observed step temperature being at approximately 270 K. Quenching by a modest applied magnetic field has been observed.

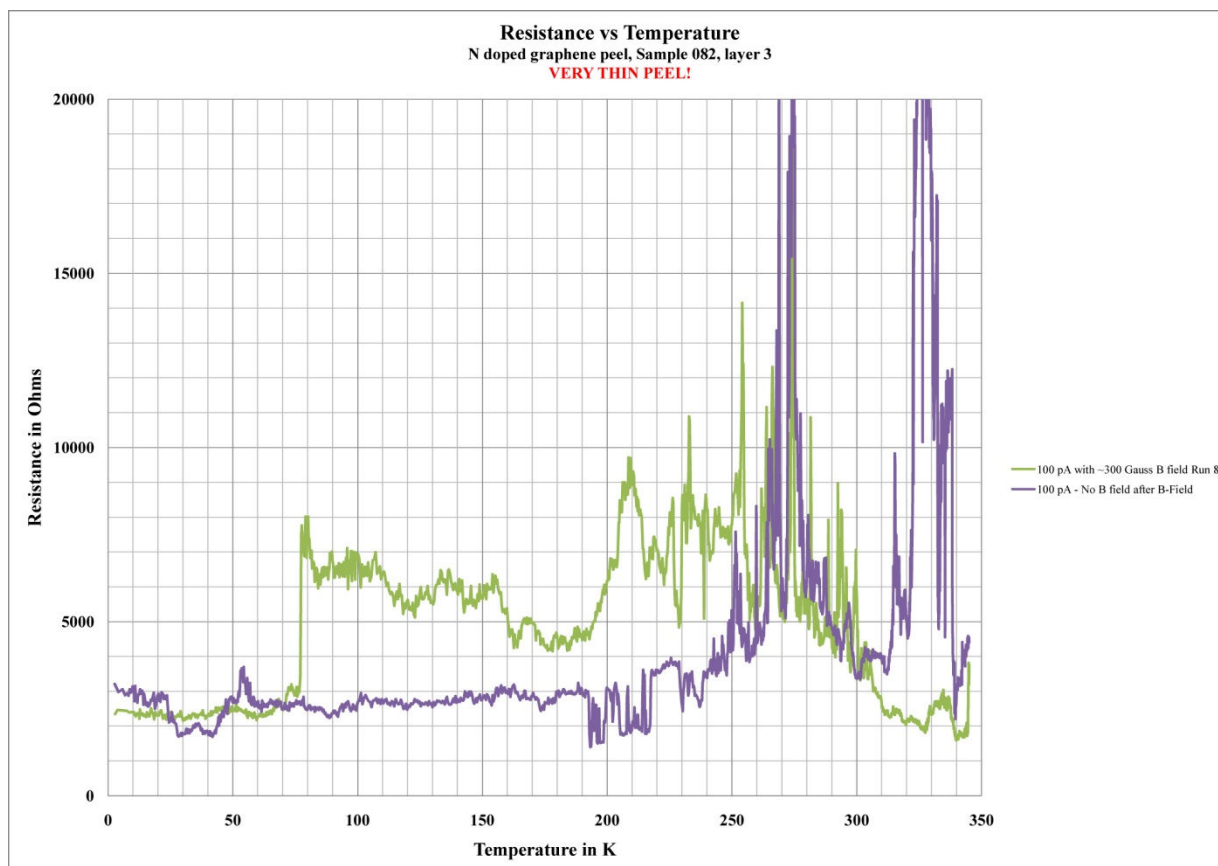
The sizes and widths of the observed steps appear to vary and may be related to some sort of aggregation reminiscent of flux vortex pinning. An additional argon ion implantation at reduced energy was done over the top of a prior phosphorous implant done to see if additional defects in the material would yield additional structure. This was observed to yield much sharper resistance steps at temperatures in excess of 200 K in thin exfoliated peels from the implanted surface of the sample and would support the possibility of the steps being related to pancake vortex pinning in a layered superconductor. Unfortunately, as yet, there has been no direct measurement of either the superconducting energy gap nor has a definitive Meissner effect been observed.

These results were published to Arxiv at: <http://arxiv.org/abs/1307.0581> . A copy of the article is attached to the e-mail that contained this document.

More recent results on very thin (<4 layers) nitrogen doped (ion implanted into Highly Oriented Pyrolytic Graphite) graphene showed a magnetic field quenching at 77K with a ~300 Gauss applied field. These are shown in the following two figures.



**Figure 1.** Resistance vs temperature on consecutive runs without external applied B field. N doped graphene. Note steps at ~60, 120, 180K. Unpublished.



**Figure 2.** Resistance vs temperature on consecutive runs (runs 8 and 9) with external applied ~300 Gauss B field on run 8. N doped graphene. Note large step at ~77K. Unpublished.

### III. Student Support:

This work supported three students, one of whom was a master's degree candidate, one of whom was a bachelor's degree candidate and one of whom is currently in the final stages of his PhD. Both the MS candidate, Gabriel Solana who has now graduated and is employed at Research in Motion, and the PhD. Candidate, Kiar Holland, are minorities (Hispanic and African American respectively). The MS. Thesis was not in the area of this research, however the student developed the data storage and interconnection network for taking data as ancillary tasks and was supported for the year in which this was being done. The PhD. is not yet complete; however the general contents of the dissertation are included in the second publication to Arxiv.